LNG Tankers and Air Emissions

Context, Inventory Methods, Implications

James Corbett, P.E., Ph.D.

5 October 2006

LNG Interagency Working Group
State Lands Commission
Marine Facilities Division
Hercules, CA 94547

First, some news …

INTERTANKO may abandon fuel oil bunkers

04 Oct 2006, 20:55 GMT

Tanker association INTERTANKO is considering stopping using fuel oil bunkers in favour of distillate fuels, the shipping weekly Fairplay reported today.

The possible move was understood to be in response to the accelerating adoption of low-sulphur restrictions under MARPOL Annex VI, such as the Sulphur Emissions Control Areas (SECAs) in the Baltic and North seas.

The additional cost to the industry would be $50 billion, the report said, and also suggested that the International Association of Dry Cargo Shipowners (Intercargo) would follow INTERTANKO's lead.

Table 2. Profile of World Fleet, Number of Main Engines, and Main Engine Power[a]

Ship Type	Number of Ships	Percent of Fleet	Number of Main Engines	Percent of Main Engines	Installed Power (MW)	Percent of Total Power	Percent of Energy Demand
Cargo Fleet							
Container vessels	2662	2%	2755	2%	43,764	10%	13%
General cargo vessels	23,739	22%	31,331	21%	72,314	16%	22%
Tankers	9098	8%	10,258	7%	48,386	11%	15%
Bulk/combined carriers	8353	8%	8781	6%	51,251	11%	16%
Non-Cargo Fleet							
Passenger	8370	8%	15,646	10%	19,523	4%	6%
Fishing vessels	23,371	22%	24,009	16%	18,474	4%	6%
Tugboats	9348	9%	16,000	11%	16,116	4%	5%
Other (research, supply)	3719	3%	7500	5%	10,265	2%	3%
Registered fleet total	**88,660**	**82%**	**116,280**	**77%**	**280,093**	**62%**	**86%**
Military vessels	19,646	18%	34,633	23%	172,478	38%	14%
World fleet total	**108,306**	**100%**	**150,913**	**100%**	**452,571**	**100%**	**100%**

[a]The world fleet represents internationally registered vessels greater than 100 gross tons; the cargo fleet represents those vessels whose main purpose is transporting cargo for trade. Percent of energy demand mainly adjusts for reduced activity (in loads and hours) by military vessels under typical operations.

Outline for Discussion

- Fleet and Propulsion Overview
- Environmental overview of ship emissions
  - Global shipping, North American inventory (3-5 slides)
  - Basics of pollutant formation, fate, transport (movie, slide)
  - Activity-based estimating methods (1-2 slides)
- Interpretation of emissions estimates
  - Emission factor and fuel comparisons (steam v. diesel)
  - Example issues in reviewing operating emissions and offsets

    …What might LNGs, other vessels and mobile sources really do?

3

Complex Maritime Transportation System

- Tug and towboats
  - 1-30 barges: 0.5 - 4 MW
- High speed ferries
  - 150-350 passengers: 2-4 MW
- Roll-on\Roll-off
  - 200-600 vehicles: 15-25 MW
- Tankers
  - 250,000 tons of oil: 25-35 MW
  - **LNG fleet: 20-30 MW**
- Container
  - 1750 TEU: 20-25 MW
  - 4300TEU: 35-45 MW
  - 6000 TEU: 55-65 MW

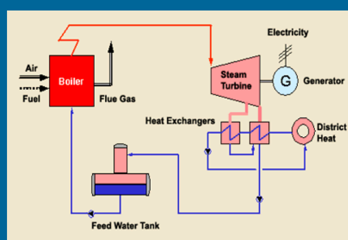
Overview of ship propulsion layouts

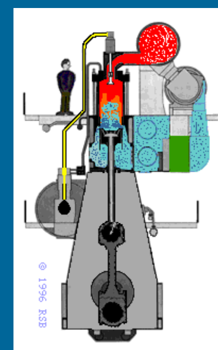
Steam Turbine Gear System

Med-speed Diesel Gear System

Slow-speed Diesel Gear System

Diesel Electric System





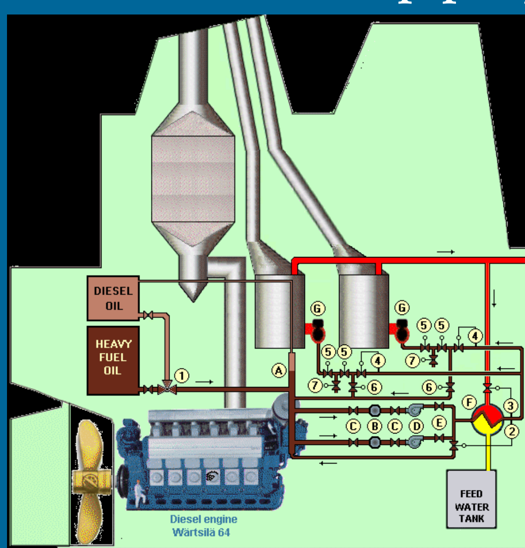
http://www.dieselduck.ca/machinery_page/diesel_engine/diesel_engine.01.htm

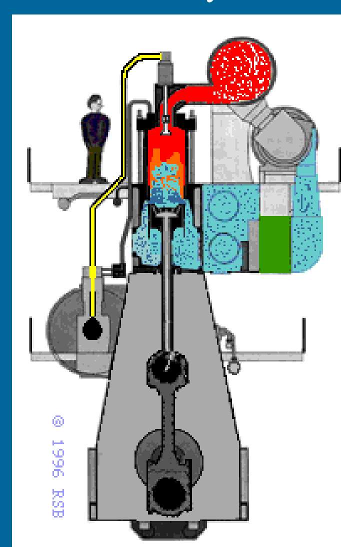
http://www.opet-chp.net/chpbackpressure.gif

http://www.dieselduck.ca/machinery_page/propulsion_layout/propulsion_layout.htm

5

Overview of ship propulsion layouts

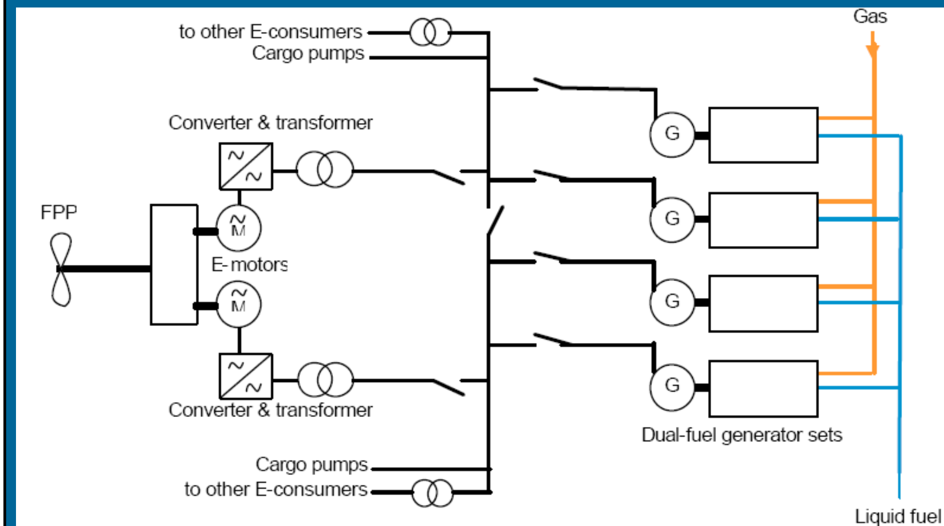




http://www.steamesteem.com/pictures/fuelsyst.gif

6

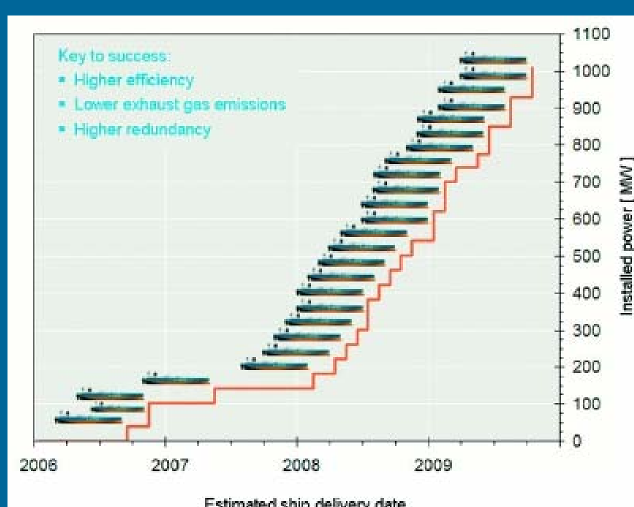
Overview of LNG propulsion layout



Wartsila: efficient_and_environmentally_friendly_machinery_systems_for_lng_carriers.pdf

7

Wartsila's expected trends

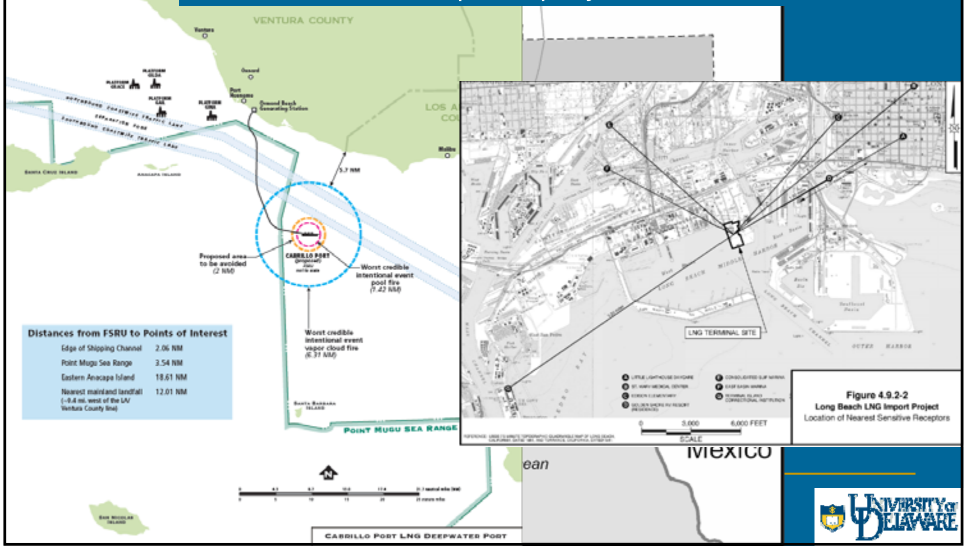


http://www.datahotelli.com/servlet/Piccolo/2006/2006_03_30.html

8

California LNG projects

- Each facility similar in size and throughput
  - ~120 to ~130 ship calls per year … or less?



Outline for Discussion

- Fleet and Propulsion Overview
- Environmental overview of ship emissions
  - Global shipping, North American inventory (3-5 slides)
  - Basics of pollutant formation, fate, transport (movie, slide)
  - Activity-based estimating methods (1-2 slides)
- Interpretation of emissions estimates
  - Emission factor and fuel comparisons (steam v. diesel)
  - Example issues in reviewing operating emissions and offsets

  …What might LNGs, other vessels and mobile sources really do?

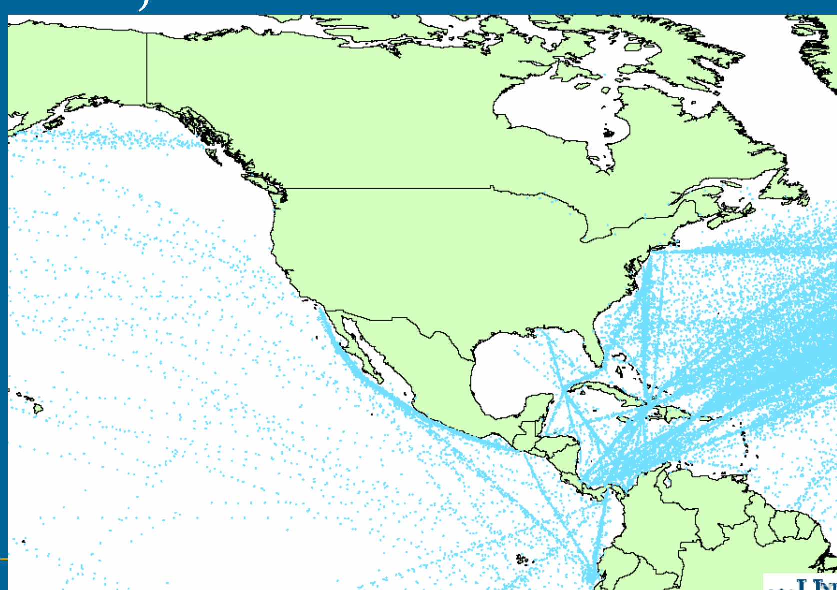
Ship traffic differs by vessel type

- Containership
- Tanker
- Bulk Carrier
- General Cargo
- Refrigerated Cargo
- Ro-Ro
- Passenger

Trade driven by commodity demand & resource supply

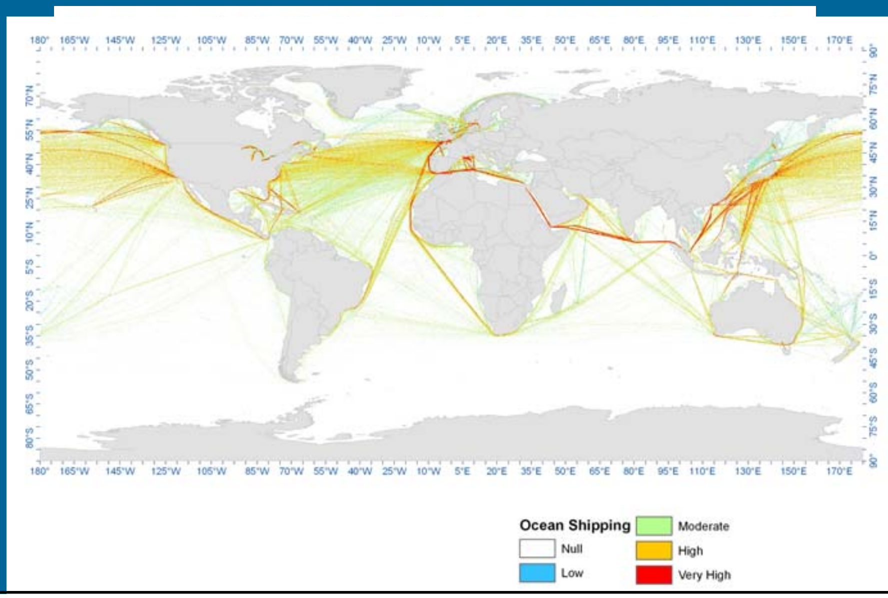
11

Unadjusted Reefer traffic



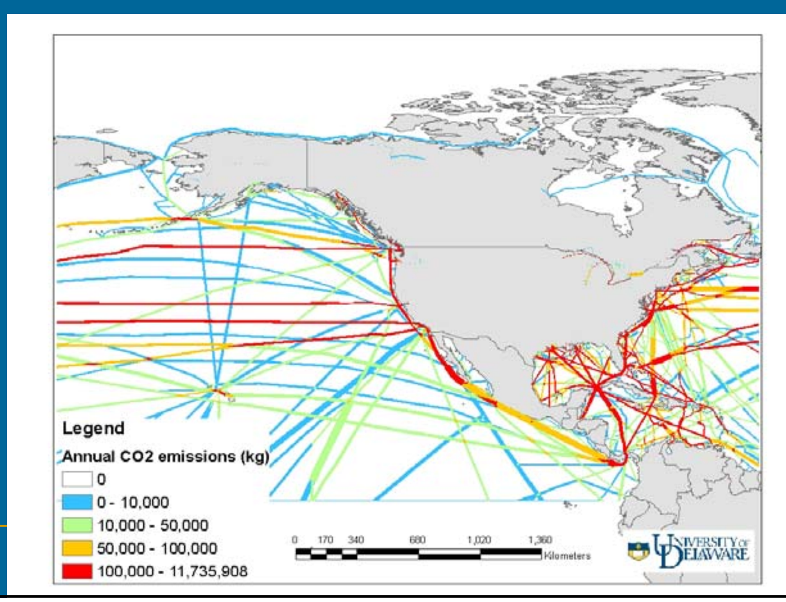
12

Trade import patterns are clear …



13

Spatial Distribution in Multimodal Context



14

Other GIS-based analyses of goods movement and environmental issues

- ***Application of Ship Speed and Mass*** to describe potential severity of risk-based ship collisions with whales
- Invasive species and ballast water treatment
- Port fees and transportation infrastructure
- ***Forecasting seaborne trade, energy, emissions***
- ***Generating multimodal routing models*** with environmental, disaster, and sustainability indices

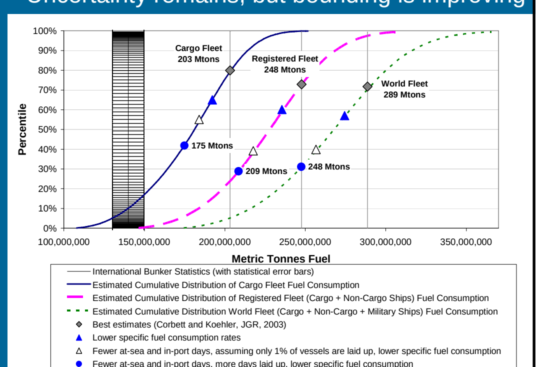
Best practices for CMV inventories

[Corbett and Koehler, 2003; Corbett and Koehler, 2004]

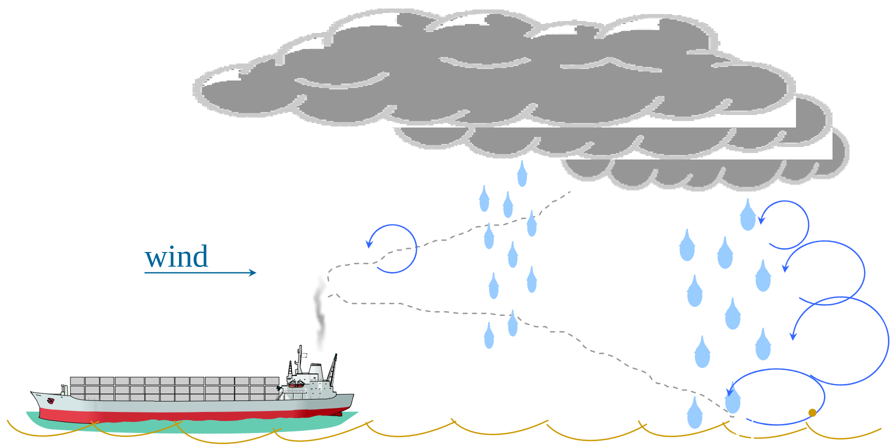
- Step 1: Identify the vessel(s) to be modeled, and engines in service
- Step 2: Estimate the engine service hours for the voyage or voyage segment
- Step 3: Determine the engine load profiles, including power and duty cycle
- Step 4: Apply emissions or fuel consumption rates for specific engine/fuel combinations
- Step 5: Estimate emissions or fuel consumption for the voyage or voyage segment

Steps 6+: Assign emissions spatially and temporally both in and out of port regions

Uncertainty remains, but bounding is improving



Atmospheric Dispersion and Removal Processes



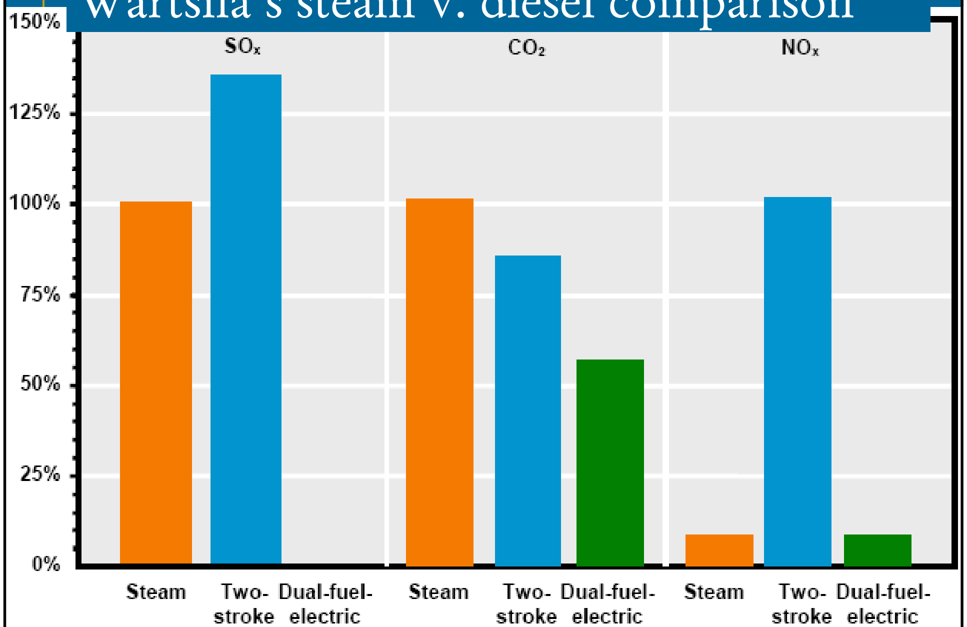
Outline for Discussion

- Fleet and Propulsion Overview
- Environmental overview of ship emissions
  - Global shipping, North American inventory (3-5 slides)
  - Basics of pollutant formation, fate, transport (movie, slide)
  - Activity-based estimating methods (1-2 slides)
- Interpretation of emissions estimates
  - Emission factor and fuel comparisons (steam v. diesel)
  - Example issues in reviewing operating emissions and offsets

  …What might LNGs, other vessels and mobile sources really do?

18

Wartsila's steam v. diesel comparison



19

Wartsila: dual fuel electric lng carrier propulsion.pdf

AP-42 data, for Nat-Gas ICEs

Internal Combustion Engines				
Industrial - Natural Gas	**lb/mm cu.ft. NG**	lb/mmBTU NG	kg/mmBTU NG	g/kWh
NOx	2840	2.65	1.20	4.10
SOx	0.6	0.00056	0.00025	0.00087
PM	10	0.0093	0.0042	0.0144
PM10	10	0.0093	0.0042	0.0144
VOC	116	0.11	0.05	0.17
CO	399	0.37	0.17	0.58
Lead	NA			

- NOx Value represents 2-stroke, lean-burn at 90-105% load.
  - At <90% load, reported as 1.94 lb/MMBtu. **4-stroke, lean-burn engines at 90-105% load is 4.08 lb/MMBtu; at <90% load, reported as 0.847 lb/MMBtu.** 4-stroke, rich-burn engines at 90-105% reported to be 2.21 lb/MMBtu; at <90% load, 2.27 lb/MMBtu.
- Reported as SO_2, using fuel sulfur content of 2,000g/10^6 scf.
- PM Value represents 2-stroke, lean-burn engines.
  - PM for 4-stroke, lean-burn engines is 7.71 E-05; for rich-burn, 9.50 E-03.
- Value reprents 2-stroke, lean-burn at 90-105% load.
  - At 90% load, reported as 0.353 lb/MMBtu. 4-stroke, lean-burn engines at 90-105% load is 0.317 lb/MMBtu; at <90% load, reported as 0.557 lb/MMBtu. 4-stroke, rich-burn engines at 90-105% reported to be 3.72 lb/MMBtu; at <90% load, 3.51 lb/MMBtu (Note higher CO for rich-burn engines).

20

AP-42 data, for Dual-fuel ICEs

	lb/hp-hr	lb/MMBtu	lb/hp-hr	lb/MMBtu	g/kWh
Dual Fuel Engine	On Diesel	On Diesel	On Dual Fuel	On Dual Fuel	
NOx	0.024	3.2	0.018	2.7	10.92
PM	0.0007	0.1	0.0007	0.1	0.42
HC as CH4	0.000705	0.09	0.00529	0.8	23.99
CO	0.0055	0.85	0.0075	1.16	4.55
CO_2	1.16	165	0.772	110	468.38

- Assumes 5% Diesel and 95% Natural Gas.
- We could also compare with ARB values for onroad use of natural gas in ICEs with and without dual fuel. These values are lower than reported above – marine engine factors for dual fuel using LNG could merit updated review.

AP-42 data, for residual fired boilers

Boiler and Diesel Emissions Compared			SFOC boiler	
Steam Boiler (average on No. 6 Fuel Oil)			290	
	lb/kgal	kg/tonnes fuel	g/kWh	
NOx (NO2)	42.5	6.03	1.75	
SO2 (S)	423.9	60.12	17.43	
SO3 (S)	15.39	2.18	0.63	SO3 negligible
CO	5	0.71	0.21	
PM	28.033	3.98	1.15	
HC (total organic carbon)	1.04	0.15	0.04	utility boilers

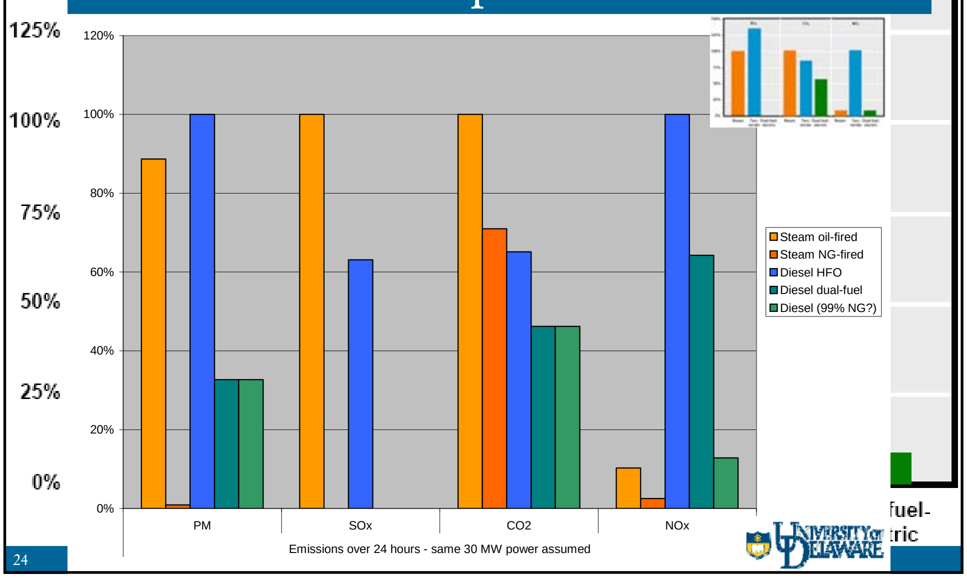
- Lower NOx factors compared to ICEs
  - Much lower than ICEs with liquid petroleum fuel
- Higher SO_2 factors – due to residual oil
  - Would fall to similar level if gas-fired
- Higher PM is clearly a function of sulfur content

AP-42 data, for natural-gas fired boilers

Boiler and Diesel Emissions Compared				SFOC boiler
Steam Boiler (average on Natural Gas)		1020	Btu/scf	
		lb/ 10^6 Btu	kg/mmBTU	g/kWh
NOx (NO2)	280	0.275	0.12	0.42
SO2 (S)	0.6	0.001	0.00	0.00
SO3 (S)				
CO	84	0.082	0.04	0.13
PM (total)	7.6	0.007	0.00	0.01
HC (total organic carbon)	5.5	0.005	0.00	0.01

- Lower NOx factors compared to oil-fired boilers
- Low SO_2 factors
- Lower PM

Wartsila's steam v. diesel comparison matches well with published factors



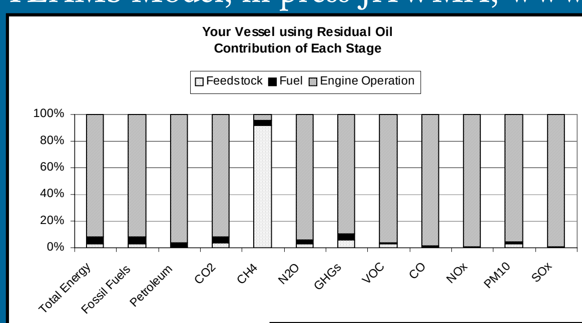
How to combine different pollutants in terms of environmental impacts? Or not …

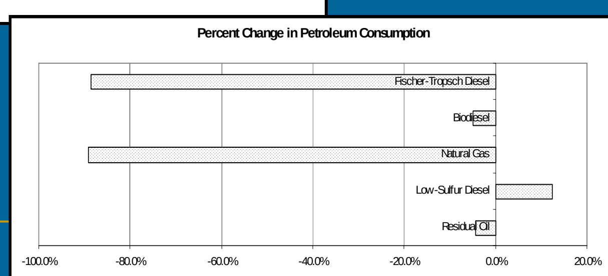
- Criteria pollutants v. climate change
- Pollutants critical to attainment
- Health risk-based pollutants

- Some combination?

Total fuel cycle comparisons may be useful

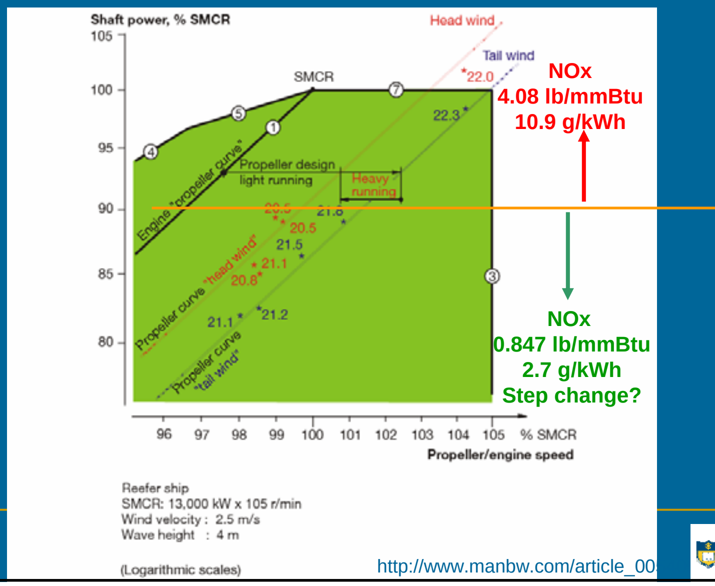
TEAMS Model, in press JAWMA, www.rit.edu/~teams





Identify possibly weak assumptions

Compare power trend with AP-42 emissions factors and with dual fuel factor



27

Outline for Discussion

- Fleet and Propulsion Overview
- Environmental overview of ship emissions
  - Global shipping, North American inventory (3-5 slides)
  - Basics of pollutant formation, fate, transport (movie, slide)
  - Activity-based estimating methods (1-2 slides)
- Interpretation of emissions estimates
  - Emission factor and fuel comparisons (steam v. diesel)
  - Example issues in reviewing operating emissions and offsets

  …What might LNGs, other vessels and mobile sources really do?

28

Take-home Ideas

- LNG fleet may be cleaner than average
  - Growing, changing power technology, emissions
- Other shipping is significant, growing also
  - Emerging rules will likely improve fleet emissions
- Emissions from alternate propulsion may be cleaner but not negligible in terms of impacts
  - Comparison varies by pollutant, energy, CO2
- Inventory best practices are sensitive to inputs
  - Emissions factors, duty cycle, fuel type
- Offsets using older technology may be easy
  - … but these may only document planned modernization

29

A modern fleet of ships does not so much make use of the sea as exploit a highway. -- Joseph Conrad, The Mirror of the Sea, Ch. 22, 1906